The Global Atmospheric Electric Circuit

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Atmospheric Electricity - reading list

- J.A. Chalmers *Atmospheric Electricity*, 2nd edition, Pergamon Press (1967)
- H. Israël (1970) *Atmospheric Electricity vol1 (Fundamentals, Conductivity, Ions)* (Problems of Cosmic Physics vol 29), Israel Program for Scientific Translations, Jerusalem.
- H. Israël (1973) *Atmospheric Electricity vol2 (Fields, charges, currents)* (Problems of Cosmic Physics vol 29), Israel Program for Scientific Translations, Jerusalem.
- D.R. McGorman and W.D. Rust, *The Electrical Nature of Storms,* Oxford University Press, Oxford, 1998.
- Krider, E.P., et al *The Earth's Electrical Environment*, Studies in Geophysics, National Academy Press, Washington, 1986 http://www.nap.edu/openbook.php?record_id=898&page=R1
- Vladimir A. Rakov and Martin A. Uman *Lightning: Physics and Effects* Cambridge University Press (2007)

Other useful resources include sections 3.31 and 10.5 of R.G. Harrison's *Meteorological Measurements and Instrumentation*, *The Feynman Lectures in Physics* (Volume III) and the PPLATO teaching resources at http://www.cse.salford.ac.uk/profiles/gsmcdonald/pp/PPLATOResources/PPLATO.htm

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Outline

1. Vertical current flow and the global circuit
2. Findings supporting the global circuit
3. Measurements of global circuit parameters
4. Variability in the global circuit
5. Applications and planetary global circuits

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Atmospheric electricity

Atmospheric electricity is concerned with:

•electrical properties of the lower and upper atmosphere
•currents flowing in the **fair weather atmosphere**
•**ionisation** of atmospheric air by natural radioactivity and cosmic rays
•**charging of particles** and droplets, snow and hail
•**charges** separated by thunderstorms and disturbed weather
•**currents** flowing from thunderstorms
•**Electric fields** in thunderstorms, the upper atmosphere and the fair weather atmosphere
•initiation of **lightning**

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0. Historical background and some key individuals

Benjamin Franklin (1706-1790) – *Statesman, a Founding Father of the US, and scientist*

Giambatista Beccaria (1716-1781) – *Professor of Experimental Physics, University of Turin*

Lord Kelvin (1824-1907) - *Experimental and mathematical physicist, University of Glasgow*

Victor Hess (1883-1964) – Austrian physicist, discoverer of cosmic rays (Nobel Prize 1936)

CTR Wilson (1869-1959) – Scottish physicist, inventor of the cloud chamber (Nobel Prize 1927)

Sir Edward Appelton (1892-1965) – English physicist and discoverer of the ionosphere (Nobel Prize, 1946)

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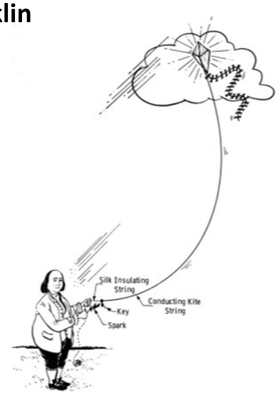
1750s - Benjamin Franklin



M.A. Uman, All about lightning, Dover, 1986

but.. debatable whether *he* actually conducted this experiment…

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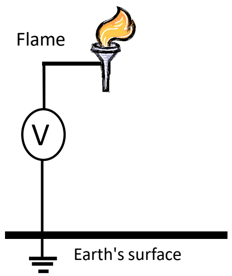
Scientific motivation: the origin of the "fair weather" field

Key finding: measurements by Lemonnier, Canton and others in 1750s detected positive electrification in fair (or "serene") weather conditions



→ *Why, in fair weather (no thunderstorms present), using a flame probe sensor, does the voltmeter record a positive voltage?*

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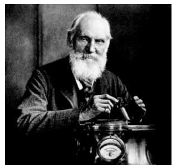
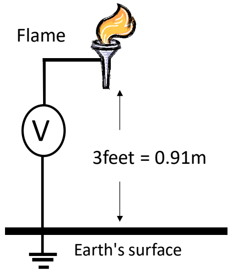
Lord Kelvin's standardised measurements



"The height of the match was 3 feet above the ground, and the observer at the electrometer lay on the ground to render the electrical influence of his own body on the match insensible. The result showed a difference of potentials between the earth (negative) and the air (positive) at the match equal to that of 115 elements of Daniel's battery."

29th meeting, British Association for the Advancement of Science, Aberdeen, September 1859



1 Daniel Cell (Zn/Cu) generates 1.08V

→ 115 Daniel cells = 124.2V

(vertical) **Potential Gradient**

Aberdeen (8am, 14th September, 1859)

= 124.2V / 0.91m = 137 Vm^{-1}

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Kelvin’s interest in the variability

“There can be no doubt but the electric indications, when sufficiently studied, will be found important additions to our means for prognosticating the weather …[I] hope to soon see the atmospheric electrometer generally adopted as a useful and convenient weather-glass” (Lord Kelvin, 18th May 1860)

Thomson, W. Reprint of papers on Electrostatics and Magnetism Macmillan, London, 1872

The variability which he observed probably challenged Kelvin’s world view, which may be the reason he sought to devise methods to investigate it – he was also central in developing telegraphy technology, which might have been affected by atmospheric disturbances

See: K.L. Aplin and R.G. Harrison, Lord Kelvin's atmospheric electricity measurements *History of Geo- and Space Sciences* **4**, 83-95, 2013 doi:10.5194/hgss-4-83-2013

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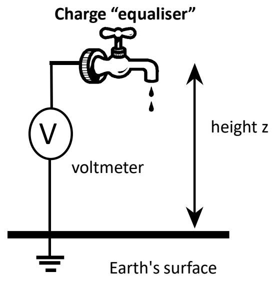
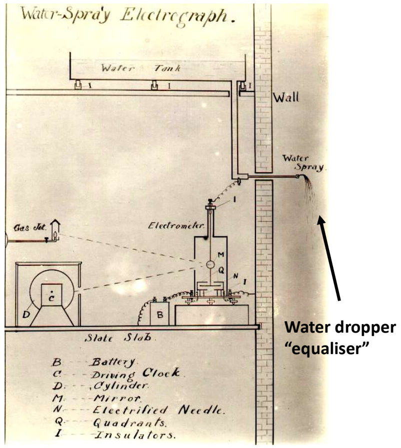
Kelvin’s “water dropper” potential equaliser





- provided continuous measurements used with photographic recording
- works by the exchange of charge between the air and the nozzle through the water droplets
- showed the PG was variable

K.L. Aplin and R.G. Harrison, Lord Kelvin's atmospheric electricity measurements, *History of Geo- and Space Sciences* **4**, 83-95, 2013

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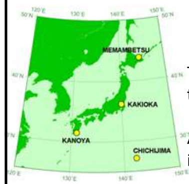
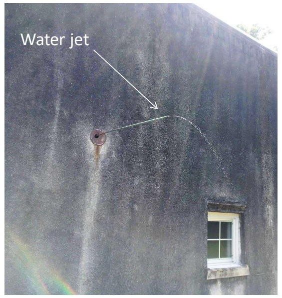
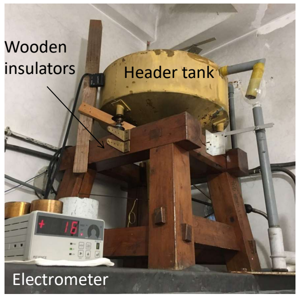
Kelvin water dropper at Kakioka Observatory



The Kelvin device was widely used, including for balloon studies and on the top of the Eiffel Tower

A water dropper sensor is still in use at Kakioka geophysical observatory in Japan





(pictures from July 2018)

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Paradigm shift around 1900

- Kelvin and others’ understanding of atmospheric electricity was based on an electrostatic view, perhaps informed by the Victorian view of an “inherited” earth system
- But…work on ionisation and current flow by C.T.R.Wilson (and, independently, by Elster and Geitel in Germany) led to the electrostatic viewpoint becoming untenable
- Evidence indicating continuing atmospheric current flow brought with it the concept of a varying, dynamic, terrestrial atmospheric electricity system

K.L. Aplin and R.G. Harrison, Lord Kelvin's atmospheric electricity measurements *History of Geo- and Space Sciences* **4**, 83-95, 2013 doi:10.5194/hgss-4-83-2013

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1. Vertical current flow in the fair weather atmosphere

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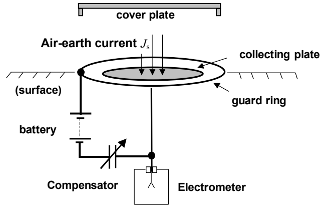
Measuring vertical current flow

Charles Thomas Rees "CTR" Wilson (1869-1959)

- **Nobel prize winner (1927) for invention of the cloud chamber**
- **also demonstrated ionisation in air (*c*1900), which implied atmospheric charge was continuously replenished through current flow**

"I remember the satisfaction I had when my work led to the fulfilment of my dream of isolating a portion of the earth's surface and measuring the charge upon it and the current flowing into it from the atmosphere."

Wilson C.T.R., 1960. Reminiscences of my early years. *Notes & Recollects Royal Society* 14, 2, 163-173



measured: **Potential Gradient** (PG) and **vertical current** density (J_c)

C.T.R. Wilson, 1906. On the measurement of the earth-air current and on the origin of atmospheric electricity. *Proc. Camb. Philos. Soc.* **13**, 6, 363-382; R.G. Harrison and W..J. Ingram, Air-earth current measurements at Kew, London, 1909-1979 *Atmos Res* **76**, (1-4), 49-64

Modern version: A.J. Bennett and R.G. Harrison, A simple atmospheric electrical instrument for educational use *Advances in Geosciences* **13**, 11-15 (2007)

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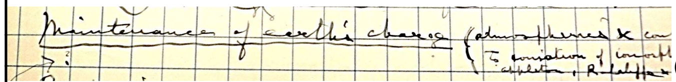
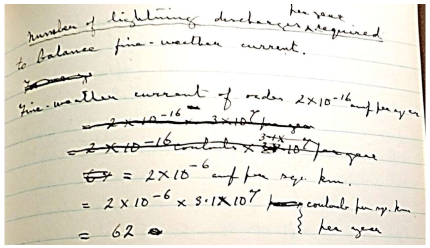
Considering global current balance – Wilson's notebooks



(A20)



"Three lightning discharges upwards per square km per year of 20 coulombs would be sufficient.

It is not impossible that even in Cambridge there may be that number of lightning strokes per square km per year."

(B8)

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Electrical conductivity of air, σ

Air is not a perfect insulator – it is weakly conducting due to presence of ions

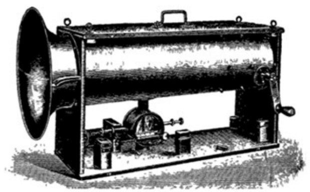
Electrical conductivity describes ability of air to conduct electric current

Coulomb discovered this property in 1785– he noticed that charge on an object decayed slowly with time

Subsequent work by Elster and Geitel 1900, and Gerdien 1905 developed instrumentation for balloons to further characterise atmospheric ions and measure conductivity

Conductivity inferred from rate of decay of charge on electrode

=> Measurement principles still used today



Balloon-borne conductivity apparatus from Gerdien (1905)

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Ionisation measurements

Early 1900s, observations showed that charge decay occurred inside electroscopes (charge measuring devices working by mechanical deflection) that were well insulated from outside (Wilson, Elster and Geitel)

What was the source of ionisation?

Ionisation due to natural radioactivity was one source – originated at ground level, therefore ionisation should decrease with height

Balloon measurements during (1911-1913) by Victor Hess showed that ionisation decreased with height for first few hundred meters, then increased

Measurements during a solar eclipse showed that the sun was not the origin of the radiation

=> Discovery of galactic cosmic rays – the lower atmosphere's principal ionising agents

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Vertical profile of air conductivity

Electrical conductivity of air results from the small ions it contains, generated by natural ion production from radioactivity and cosmic rays

$$\boxed{\sigma = 2\, n\, \mu\, e}$$

σ =total conductivity

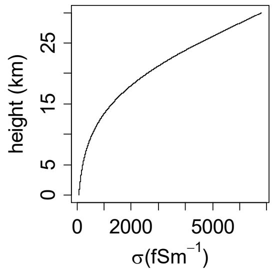
n = ion number concentration

μ = ion mobility

e = electronic charge

Typically σ ~$10^{-14}\ \Omega^{-1}\ m^{-1}$ in surface atmospheric air, or using SI ~ 10 fS m^{-1}

Only **small** ions (d ~1nm) contribute to σ



Ion production rate varies with height (decreasing terrestrial ionisation but increasing cosmic ionisation)

Ion mobility also varies with temperature and pressure

→ Conductivity profile

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Columnar resistance, R_c

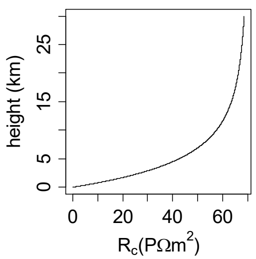
•Columnar resistance is the found from the reciprocal of conductivity σ(z)

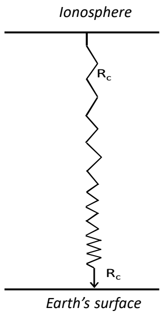
•Expressed as an integrated resistance, of a unit area column of air:

$$\boxed{R_c = \int_0^{z_I} \frac{dz}{\sigma(z)}}$$

•z = altitude
•z_I = height of upper conducting layer

•R_c~ 50 to 300 PΩ m²





•most of R_c contribution is from lowest few km of atmosphere

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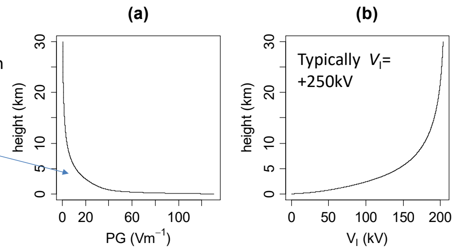
Ionospheric potential - V_I

•The potential increases with height, to a maximum value essentially constant from the stratosphere to the ionosphere – known as the **ionospheric potential** V_I

•V_I is found from integrating the vertical profile of PG, measured by radiosonde balloons or aircraft, carrying a field mill or radioactive collectors. It is essentially a **global equipotential**

most variation in potential is within the lowest 10km



If the PG at height z is written as $F(z)$ $\quad V_I = \int_0^{z_I} F(z)\, dz$

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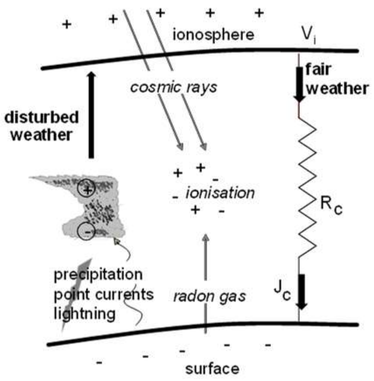
Local to global - Wilson's "global circuit" conceptual model

Wilson's "global atmospheric electric circuit", describes electrical characteristics of the atmosphere:

Source: ***Thunderstorms and rain clouds*** *transfer positive charge to the ionosphere in disturbed weather regions*

Sink: *In fair weather regions the air-earth current density J_c returns a small "conduction current" to Earth .*

- •Atmosphere bounded by upper and lower "conducting" layers
- •Global thunderstorms and rain clouds charge upper layer to ~ + 300kV (V_I)
- •Vertical current density J_c (~ 2pAm^{-2}) of cluster ions flows in fair weather regions
- •Unit area "Columnar resistance" R_c ~ 150PΩm^2



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2. Findings supporting the global circuit concept

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Ocean measurements: the *Galilee* and *Carnegie*

The *Galilee* and *Carnegie* were the Carnegie Institution of Washington's geophysical survey ships. The *Galilee* was ultimately unsuitable as some magnetic parts could not be replaced; the *Carnegie* was a replacement constructed specially, built from wood, copper and bronze, with an observing deck

Galilee – brigantine built in 1891, as a fast packet between San Francisco and Tahiti. Chartered by CIW in 1905.

Carnegie under full sail in 1909 at launch. From 1909 to 1929 she covered 500,000km, and made the fastest circumnavigation of Antarctica.

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Difficulties with early instrumentation

•Atmospheric electricity development work was delayed, until the final cruise of the *Galilee.*

•These first measurement attempts proved very difficult. In particular, the atmospheric electric field (Potential Gradient, PG) measurements…

"…seemed quite impracticable…the rolling of the ship, the flapping of the sails, and the varying position of the yards and boom under various sailing conditions all contributed to make the problem of reducing observations of potential-gradient to a uniform basis too complicated…" [CIW175v3, p364]

R.G. Harrison, The Carnegie Curve *Surv Geophys* **34**, 2, 209-232, DOI: 10.1007/s10712-012-9210-2 (2013)

•Of several atmospheric electricity instruments considered for the *Galilee* (e.g. the Ebert ion counter) only air conductivity measurements, using a Gerdien aspirated device, showed practical promise.

•Air ion measurements were made on cruise I of the *Carnegie* (1909-1910), alongside observations of "specific conductivity" and "radioactive content".

Ion content of the atmosphere, 1911 (CIW)

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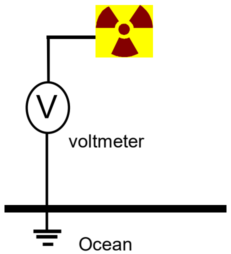
Potential Gradient sensors

Principle: radioactive "collector" methods to acquire local potential



Carnegie cruise 2 (1910-1913)
Kidson and Johnston used two radium collectors suspended on a bamboo pole, extending aft from the stern rail; Hewlett tried ionium (^{232}Th) collectors

Carnegie cruise 3 (June 8th 1914 to Oct 21st 1914)
PG used ionium collectors suspended on a bamboo pole, extending aft from the stern taffrail; standardization achieved by simultaneous ship and shore observation on two occasions, at Reykjavik and Gardiners Bay: average PG for whole cruise 93 Vm^{-1}

Carnegie cruise 4 (1915-1916)
special "atmospheric-electric" house built aboard to reduce set up time, and keep instruments in stable conditions, but the ionium coated collector plate on bamboo pole took too long (~2min) to come within 1V of the final steady potential

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Mechanical Potential Gradient sensor

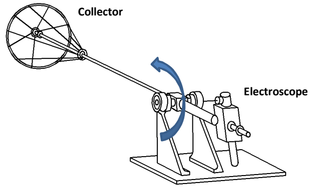
A new faster electric field measurement method was developed, which also compensated for tilt of ship

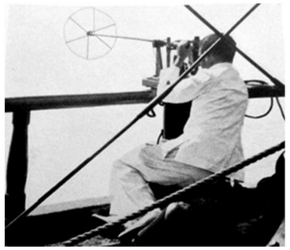
-a "parasol" collector was constructed from gauze on a pivot arm, to allow it to be adjusted for ship angle.

-Rotated from an earthed (pointing downwards) position, to horizontal to horizon, and **change in electroscope** reading recorded. (Hourly data)

-sustained good quality insulation was not needed; used sulphur insulators. The handle's hard rubber insulation was more critical, and had to be kept clean. Daily leakage tests

-battery offset for electroscope could also be applied





R.G. Harrison, The Carnegie Curve *Surv Geophys* **34**, 2, 209-232, DOI: 10.1007/s10712-012-9210-2 (2013)

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Diurnal cycle results from Cruises 4, 5 and 6

By 1921, using harmonic analysis on the previous decade's data, the principal contributor to the PG's diurnal variation was a 24 hour component, and it was reported by its discoverer, the Carnegie Institution's S.J. Mauchly, that

*"...the 24 hour Fourier wave was at the great majority of land stations in practical phase agreement on **universal time** with the prime daily wave over the oceans without regard to location.* [CIW175v5,p387]

This indicated that the origin of the potential gradient was not local

Mauchly SJ, Note on the diurnal variation of the atmospheric electric potential gradient *Phys Rev* n.s. **18**, 161-162 (1921); Mauchly SJ, On the diurnal variation of the potential gradient of atmospheric electricity *Terr Mag* **28**, 61-81 (1923)

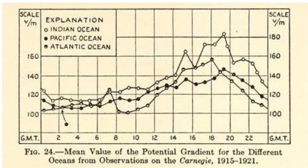

Fig. 24.—Mean Value of the Potential Gradient for the Different Oceans from Observations on the *Carnegie*, 1915–1921.

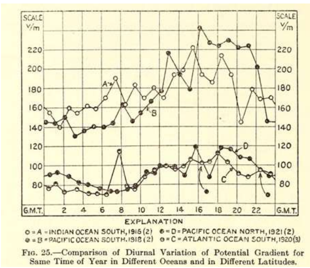

Fig. 25.—Comparison of Diurnal Variation of Potential Gradient for Same Time of Year in Different Oceans and in Different Latitudes.

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Motivation for Cruise 7

Further frequent and widely distributed varying atmospheric electricity measurements were still sought

"...to settle the question whether such variations progress on the basis of universal time" (Ault, 1927).

A key improvement on the earlier cruises proposed was to employ continuous recording techniques, using a projection electrometer with photographic chart recording.

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Cruise 7: oceanography and meteorology

Ault taking off "Nansen bottle", used to sample deep-sea water, 1928.

Pilot balloon weighing, prior to ascent, 1928

Ault releasing pilot balloon, to measure upper air currents, 1928.

Sighting on pilot balloon with sextant and theodolite, 1929

Ault in diving helmet, going down to disentangle bottom sample wire from hull, 1929

Carnegie Institution of Washington

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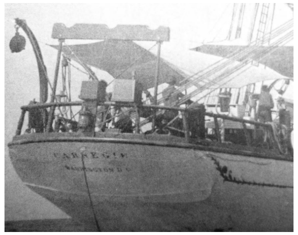
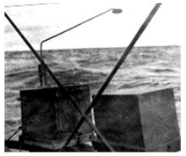
Continuous PG recording on Cruise 7

- Initially a sensor with continuous recorder was planned for the masthead, but became impractical from flexing of the hemp rigging.
- Site adjacent to the parasol collector on the stern rail used instead.





Bent collector rod used initially, projecting out over the water astern. (7th July 1928 to Nov 5th 1929)

Vertical collector installed Nov 5th 1929.

Collectors in amber, 75cm above weatherproof wooden box housing fibre electrometer, microscope, light source, and motorised photographic recorder

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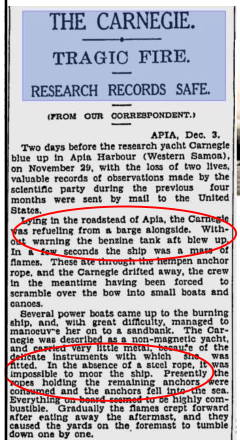
Cruise 7 - tragedy



THE CARNEGIE.

TRAGIC FIRE.

RESEARCH RECORDS SAFE.

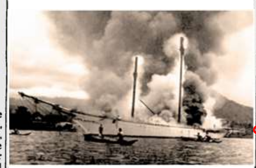
(FROM OUR CORRESPONDENT.)

APIA, Dec. 3.

Two days before the research yacht Carnegie blue up in Apia Harbour (Western Samoa), on November 29, with the loss of two lives, valuable records of observations made by the scientific party during the previous four months were sent by mail to the United States.

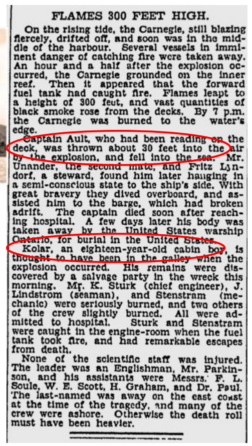
Lying in the roadstead of Apia, the Carnegie was refueling from a barge alongside. Without warning the benzine tank aft blew up. In a few seconds the ship was a mass of flames. These ate through the hempen anchor rope, and the Carnegie drifted away, the crew in the meantime having been forced to scramble over the bow into small boats and canoes.

Several power boats came up to the burning ship, and, with great difficulty, managed to manoeuvre her on to a sandbank. The Carnegie was described as a non-magnetic yacht, and carried very little metal, because of the delicate instruments with which she was fitted. In the absence of a steel rope, it was impossible to moor the ship. Presently the ropes holding the remaining anchors were consumed and the anchors fell into the sea. Everything on board seemed to be highly combustible. Gradually the flames crept forward after eating away the aftermast, and they caused the yards on the foremast to tumble down one by one.



November 29th, 1929, Apia Harbour (*Carnegie Institution*)

"The story of individual endeavour and enterprise, of invention and accomplishment, cannot be told." Captain J.P. Ault (August 26th, 1929) *Carnegie Institution of Washington Publication* 568, page iii



FLAMES 300 FEET HIGH.

On the rising tide, the Carnegie, still blazing fiercely, drifted off, and soon was in the middle of the harbour. Several vessels in imminent danger of catching fire were taken away. An hour and a half after the explosion occurred, the Carnegie grounded on the inner reef. Then it appeared that the forward fuel tank had caught fire. Flames leapt to a height of 300 feet, and vast quantities of black smoke rose from the decks. By 7 p.m. the Carnegie was burned to the water's edge.

Captain Ault, who had been reading on the deck, was thrown about 30 feet into the air by the explosion, and fell into the sea. Mr. Unander, the second mate, and Fritz Lyndorf, a steward, found him later hanging in a semi-conscious state to the ship's side. With great bravery they dived overboard, and assisted him to the barge, which had broken adrift. The captain died soon after reaching hospital. A few days later his body was taken away by the United States warship Ontario, for burial in the United States.

Kolar, an eighteen-year-old cabin boy, is thought to have been in the galley when the explosion occurred. His remains were discovered by a salvage party in the wreck this morning. Mr. K. Sturk (chief engineer), J. Lindstrom (seaman), and Stenstram (mechanic) were seriously burned, and two others of the crew slightly burned. All were admitted to hospital. Sturk and Stenstram were caught in the engine-room when the fuel tank took fire, and had remarkable escapes from death.

None of the scientific staff was injured. The leader was an Englishman, Mr. Parkinson, and his assistants were Messrs. F. L. Soule, W. E. Scott, H. Graham, and Dr. Paul. The last-named was away on the east coast at the time of the tragedy, and many of the crew were ashore. Otherwise the death roll must have been heavier.

The Sydney Morning Herald - Dec 13th, 1929

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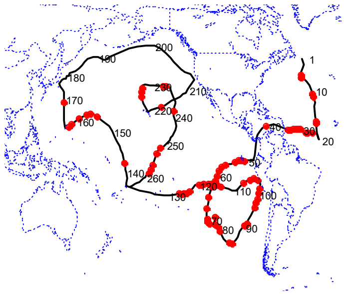
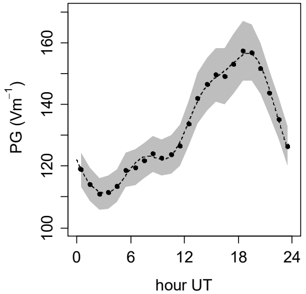
Cruise 7 observations



Number of days from outset marked: red points are those days which were subsequently identified as electrically undisturbed



•From Aug 7th 1928 to Nov 18th 1929 the Carnegie was on open sea for 317 days, yielding 181 days of continuous PG data

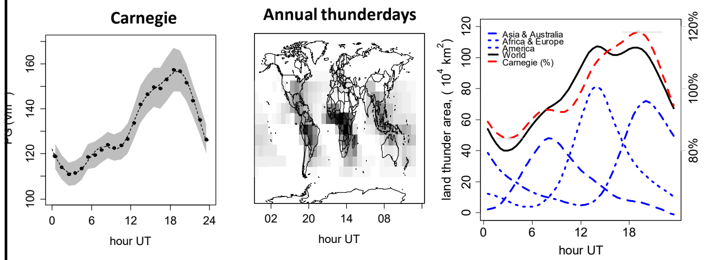
•5 reduction factor experiments (Kitts Point, (Maryland), Engey Island, (Reykavik), Bridgetown, (Barbados) Easter Island and Apia, Samoa)

R.G. Harrison, The Carnegie Curve *Surv Geophys* **34**, 2, 209-232, DOI: 10.1007/s10712-012-9210-2 (2013)

32

GEC explanation of the Carnegie curve

- corrected to GMT (UTC), the PG diurnal variation timing was independent of the ship's location, implying a global origin
- Thunderstorm data ("thunderdays") compiled from global meteorological stations to investigate this



- Whipple and Scrase (1936) found the phase of the Carnegie curve agreed closely with that of the global hourly thunderstorm area

See also: R.G. Harrison, Behind the curve: a comparison of historical sources for the Carnegie curve of the global atmospheric electric circuit, *Hist. Geo Space Sci* 11, 207-213, 2020 https://hgss.copernicus.org/articles/11/207/2020/

33

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Radiowave confirmation of conducting layers

- If upper and lower spherical layers exist, they would provide a resonant cavity for electromagnetic waves, such as those excited by lightning discharges
- Schumann (1952) predicted that, for two concentric conducting spheres, the **Schumann resonance** frequency would be

$$f_n = \frac{c}{2\pi R_E}\sqrt{n(n+1)}$$

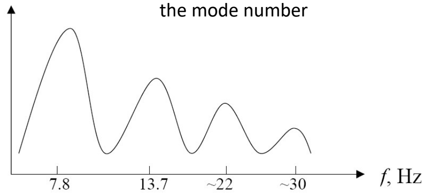
where c is the speed of light, R_E the radius of the earth and n the mode number

f_1 is predicted to be in the ELF at about 8Hz – this was found by Balser and Wagner (1962) at 7.8Hz

Small signal:

E ~300µV m^{-1}

B ~pT

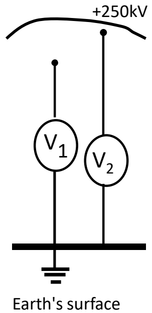


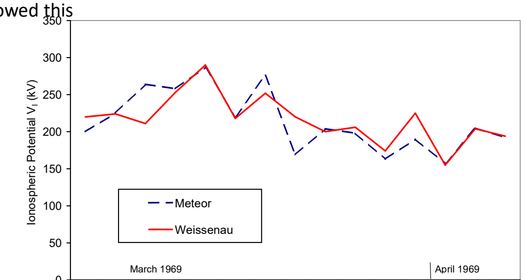
34

34

Corroboration of upper equipotential

- If there is an equipotential upper layer, the potential should be similar at different locations
- Simultaneous soundings from Weissenau (Germany) and the research ship *Meteor* in the Atlantic showed this





day of month:	17	18	19	20	20	21	21	28	29	29	30	30	2	2	2
Meteor	200	225	264	258	287	220	276	169	204	198	163	190	157	205	192
Weissenau	220	224	211	253	290	218	252	220	200	206	174	225	155	204	194

- Muelheisen R.P. 1971. New determination of the air-earth current over the ocean and measurements of ionospheric potentials. PAGEOPH 84, 112-115
- Budyko, M.I., 1970. Results of observations of atmospheric electricity (The World Network, Additional Issue 1965-1969). USSR Chief Administration of the Hydro-Meteorological Service, Leningrad

35

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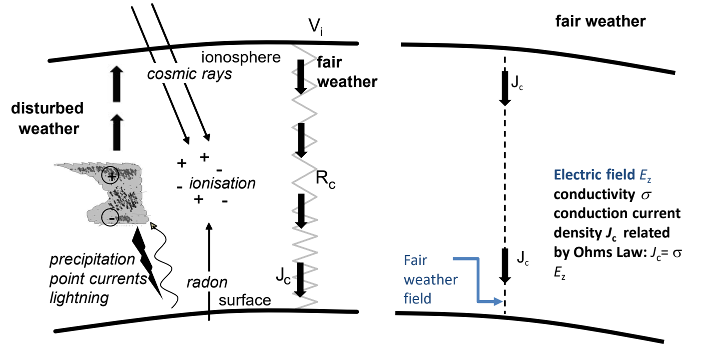
GEC resolves long standing question - origin of "fair weather field"

Current flows vertically in the fair weather atmosphere due to the *global circuit*…



R.G. Harrison, K.A. Nicoll, M.H.P. Ambaum, On the microphysical effects of observed cloud edge charging *Quart Jour Roy Meteorol Soc* 141, 2690-2699, doi:10.1002/qj.2554 (2015)

36

3. **Measurements of global circuit parameters**

1. Potential Gradient (field mill, long wire antenna)
2. Air-earth current (Wilson apparatus, Lerwick plate, and GDACCS)
3. Air conductivity
4. Fair weather classification

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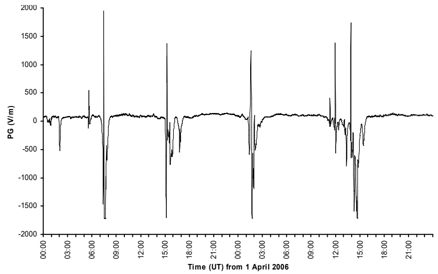
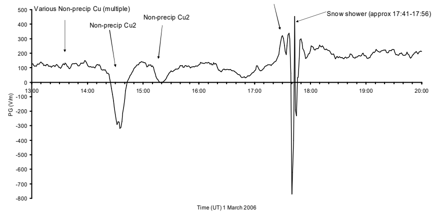
PG - a very variable quantity

- With **thunderclouds** present, the PG obviously becomes highly variable.
- **But convective showers** and rainfall also lead to considerable variability
- And…even with low level layer cloud - no ice and minimal convection - the PG can be quite variable – is it due to space weather, or earth weather? --> reliable series of measurements are needed.





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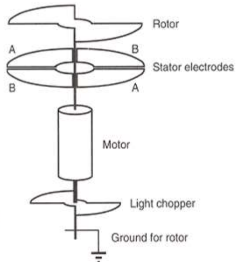
The field mill

•Robust and durable instrument for measuring atmospheric **electric field**

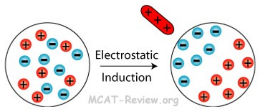
•Horizontal plate electrode in which a charge is induced by the atmospheric electric field

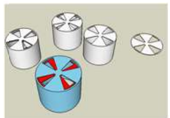
•This is compared with the charge induced under zero electric field conditions (when electrode covered).

=> Electrode is alternately covered and exposed by a mechanical shutter, which is driven by a motor – **synchronous detection** used to detect changes.



Operates continuously at the Observatory – see the real time graphs





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Commercial field mills

- Electric field mills now widely commercially available
- Not so for other atmospheric electricity instruments

Boltek EFM100

Campbell CS110

Chilworth JCI131

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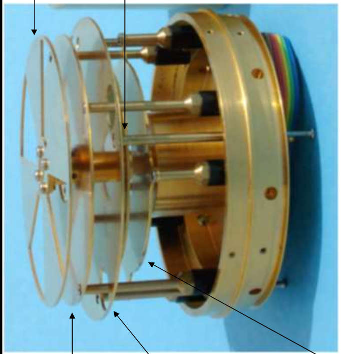
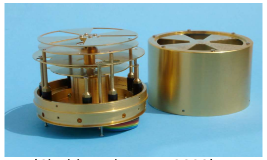
primary
chopper

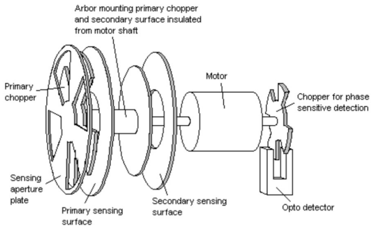
secondary
rotating surface

JCI131 Brushless fieldmill





(Chubb and Pavey, 2009)



(Chubb, 1999)

primary
sensing surface

screen (to chassis)

secondary
sensing surface`

41

Miniaturised electric field sensors

Increased need for lightweight miniaturised electric field sensors for balloon and UAV

Bateman, M. G., et al. "A low-noise, microprocessor-controlled, internally digitizing rotating-vane electric field mill for airborne platforms." *Journal of Atmospheric and Oceanic Technology* 24.7 (2007): 1245-1255.

Alex Kochin
Central Aerological Observatory
Roshydromet

- Flown on many manned aircraft and UAV (Altus II) campaigns

- Many other prototype field mills under development by AE researchers

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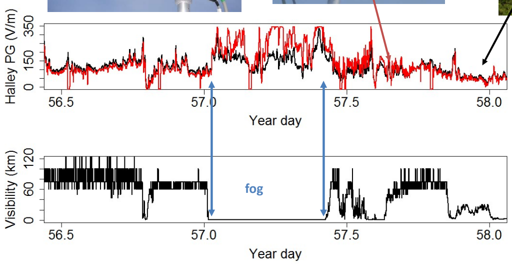
Instrument limitations - Antarctica

- Formation of fog (and sub zero temperatures) led to frost build up (riming) on British Antarctic Survey's own design of field meter



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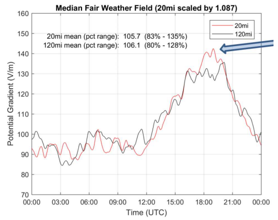
Ocean buoy measurements

Deployed off the coast of Florida, near Titusville (north of Kennedy Space Centre field mill network)



10 second samples in FW, 1 second samples when disturbed; Iridium satellite data transfer

(From Ken Cummings, University of Arizona)

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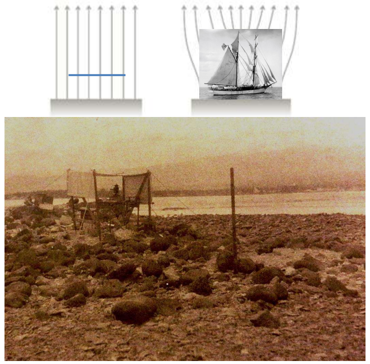
Standardisation – e.g. corrections for ship distortion

•On the **Carnegie voyages**, a "reduction factor" was needed to correct for the distortion of the ship and its rigging

•comparison made with flat shore sites close to level with the sea, free from trees, using a 15 to 20m long horizontal "passive wire" antenna

•Difficulty was in getting ship within half-mile…so reduction factor was measured often and averaged

•Reduction factor practically constant for PG 120 to 480V m^{-1}, 2.85 for mainsail up and boom to port or starboard, and 3.77 for mainsail down, with boom over port crutch



Potential Gradient "reduction-factor station", Watson's Island, Apia, Samoa (April 1929). Spiders caused frequent trouble by spinning webs in the cap of the shore electrometer and in the caps of the supporting insulators of the stretched wire system. "The spiders were numerous. Several hours of record were affected by the presence of spider webs."

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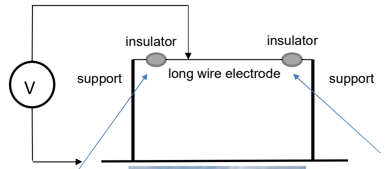
Passive wire antenna

•Ultra well-insulated horizontal wire positioned at known height naturally acquires the potential of the atmosphere



•Rate of acquisition of potential on the wire is not artificially accelerated by an equaliser
=> instrument is called the **passive wire**

• Wire potential measured using a high impedance voltmeter

•No calibration or geometrical corrections required as long as there are no distorting objects nearby =>value of PG at 1m measured using passive wire is considered absolute

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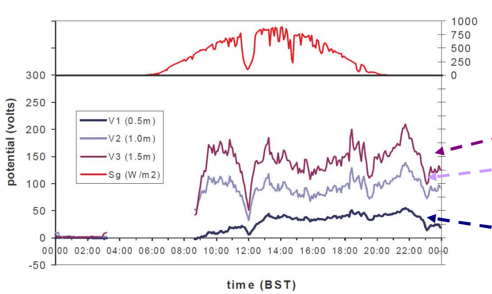
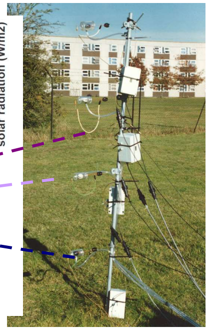
Vertical array of passive antennas





•Potential increases positively with height

•Continuous turbulent mixing of ions is required for effective operation

•Note the effect of a cloud passing around noon BST

J.F. Barlow and R.G. Harrison (1999) Turbulent transfer of space charge in the atmospheric surface layer, *Proceedings Int Conf Atmos Elect, Huntsville Alabama*

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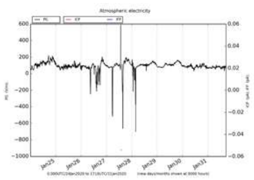
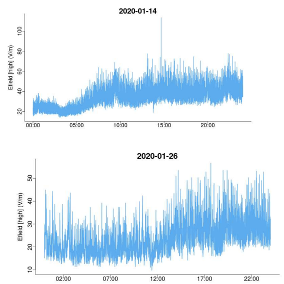
Cruise of the NRP* Sagres

**Navio da República Portuguesa*





https://www.vesselfinder.com/vessels/PT-NAVY-SAGRES-IMO-0-MMSI-263141000

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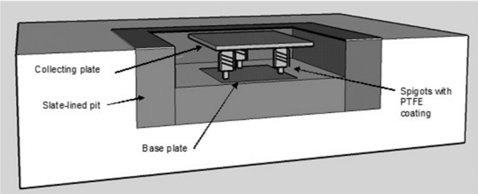
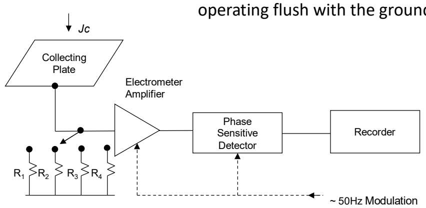
Conduction current – the Lerwick plate



Schematic of 0.5m² air-earth current collecting plate, operating flush with the ground in a slate-lined pit



Block diagram of electronic system. (*Input resistor values:* R1 10GΩ, R2 25 GΩ, R3 50 GΩ, R4 100 GΩ.)

R.G. Harrison and K.A. Nicoll, Air-earth current density measurements at Lerwick; implications for seasonality in the global electric circuit *Atmospheric Research* **89**, 1-2, 181-193, doi:10.1016/j.atmosres.2008.01.008

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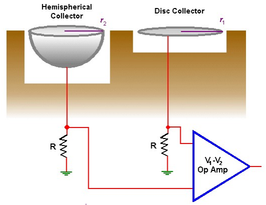
Vertical current density instrumentation



Mukku, V. N. R., (1984). A design for eliminating displacement currents in the air-earth current measurement, *Journal of Physics* **17**(E) 629.

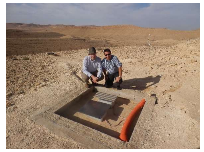
displacement current J_D – proportional to total area - and conduction current J_c – proportional to cross section

Reading "GDACCS" instrument uses two electrodes with different geometry

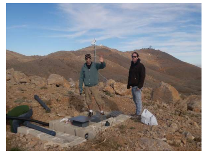
- heated, to repel water and insects

Bennett, A.J. and Harrison, R.G., (2008). Surface measurement system for the atmospheric electrical vertical conduction current density, with displacement current density correction, *J Atmos & Solar-Terrestrial Physics* **70** 1373–1381.

Reading



Negev



Mt Hermon

50

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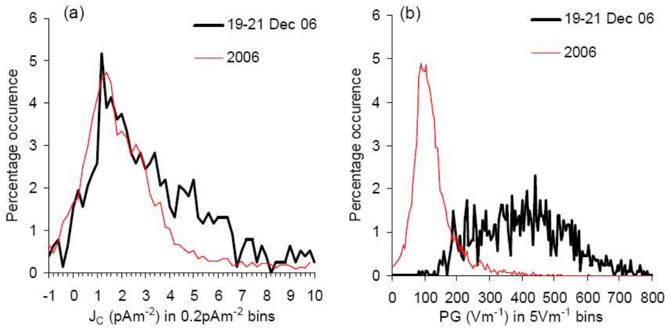
J_c and PG measured during fog



A.J.Bennett Measurements of Atmospheric electricity during different meteorological conditions, PhD Thesis, Reading, 2007

- Vertical current density affected little by fog layer
- PG greatly affected by low conductivity of foggy air

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Changes in electrical parameters during fog

Quantity	Fair weather (FW)	Foggy	Ratio foggy/FW
Conduction current density	1.4 pAm^{-2}	1.2 pAm^{-2}	0.9
Potential Gradient	100 Vm^{-1}	400 Vm^{-1}	4.0
Air conductivity (calculated)	14 fSm^{-1}	3 fSm^{-1}	0.2

Table 5-1. Comparison of Ohm's Law parameters in foggy and fair weather.

- PG in fog is ~4 to 5 times larger than FW
- PG measurements in fog can be used to estimate in fog conductivity

→ Conductivity in fog ~ 5 times smaller than clear air

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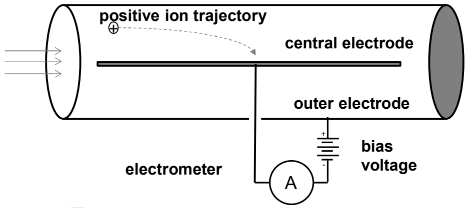
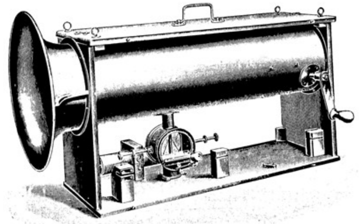
Air conductivity measurements by "Gerdien" sampling tube

$$\sigma_{\pm} = \frac{i\varepsilon_0}{CV_{\pm}}$$





Gerdien's condenser (1905)

- clockwork fan
- fibre electrometer
- brass electrode, ebony and amber construction
- voltage decay method to infer current
- designed for balloon experiments

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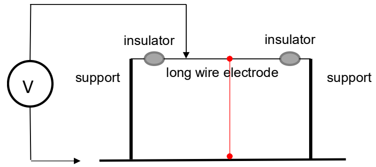
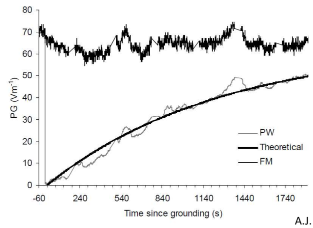
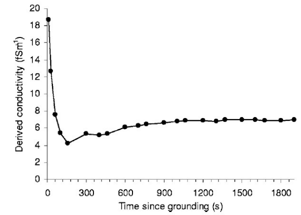
Passive wire conductivity method

Ground the passive wire and measure the charging time constant τ



Conductivity is found as $\sigma = \frac{\varepsilon_0}{\tau}$

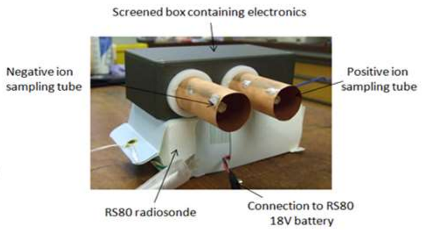




A.J. Bennett and R.G. Harrison, In situ calibration of atmospheric air conductivity measurements *Rev Sci Instrum* **77**, 016103 (2006)

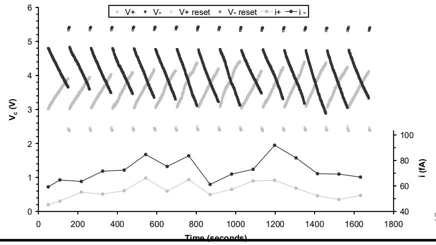
54

Balloon carried polar conductivity sensor



- Electronic developments has allowed miniaturisation of sensors
- Dual sampling tubes allow simultaneous measurement of σ_+ and σ_-
- Sensors can be flown alongside standard radiosondes, with data transmitted in real time

K.A. Nicoll and R.G. Harrison, A double-Gerdien instrument for simultaneous bipolar air conductivity measurements on balloon platforms, *Rev Sci Instrum* **79**, 084502 (2008)



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4. Variability in the global circuit

The global circuit is a planetary framework of electrical connectivity – it will also reflect variability of different kinds occurring in the atmospheric system, e.g.

- **Internal variability**. Changes in the thunderstorm and shower clouds which drive it, in terms of their positions and contributions. ENSO may influence these
- **External variability**. Cosmic rays provide much of the conductivity of air away from the surface. Factors which modulate cosmic rays – primarily solar changes – will lead to changes in the current flow.

This will **couple through into atmospheric processes** which use the global circuit in some way.

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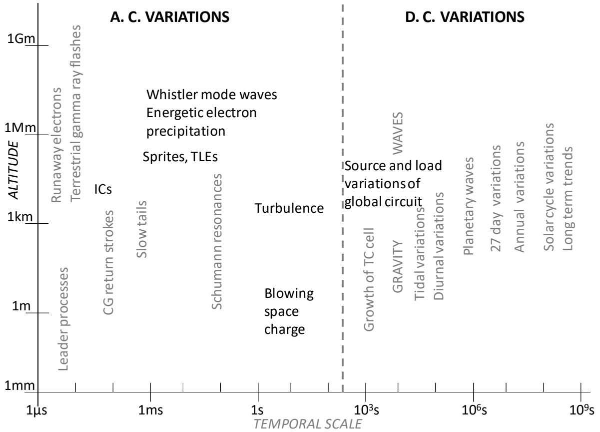
Global circuit variability



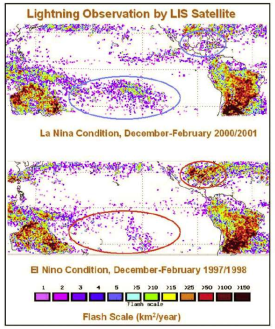
M.J. Rycroft, K.A. Nicoll, K.L. Aplin and R.G. Harrison, Recent advances in global electric circuit coupling between the space environment and the troposphere *J.Atmos Sol-Terr Phys* 90–91, 198–211 (2012),

57

ENSO effects on lightning

•Intensity, flash rate and location of lightning varies with ENSO timescale

•10% change in global lightning flash rate from La Niña to El Niño



More lightning in Pacific during(cool) La Niña phase than (warm) El Niño

Complex relationship between regional variations in lightning and El Niño, La Niña . i.e. very location dependent

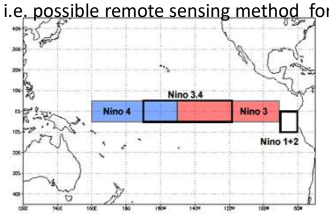
Satori G., et al, Variability of global lightning activity on the ENSO time scale, Atmospheric Research, 91, 500-507, 2009

58

ENSO effects on surface PG

GEC integrates effects of all thunderstorms active around globe

Signals from large scale variations may be seen in distant PG measurements i.e. possible remote sensing method for electrically active storms

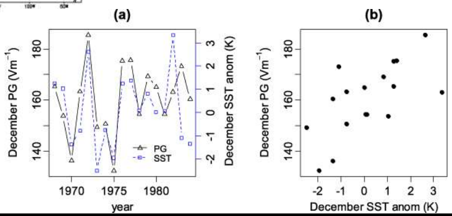


Lerwick PG measurements compared to Niño 3.4 index (SSTs from area in Pacific ocean, bounded by 5°N-5°S and 120°-170°W)

Image from www.ncdc.noaa.gov

Remarkably strong correlation – PG large during El Niño and small during La Niña

Increase in GEC of 3.5% for 1K of SST anomaly



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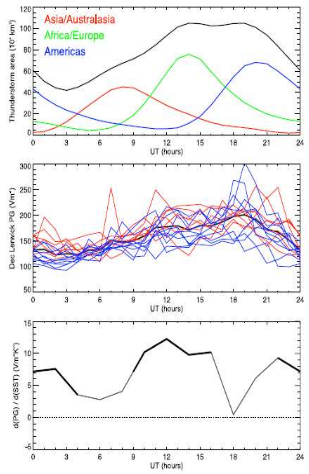
ENSO: Internal variability and Carnegie curve

El Niño Southern Oscillation shows a relationship with the Carnegie curve of the global circuit in atmospheric electricity – mean values increase with Pacific sea surface temperature

Red lines show Carnegie curve in atmospheric electricity at Lerwick (for December) during **El Niño** conditions, and *blue lines* during *La Niña*

→ sensitivity of ~ 5 $Vm^{-1}\ K^{-1}$

Greatest PG sensitivity to SST change is between 10-16UT => African lightning



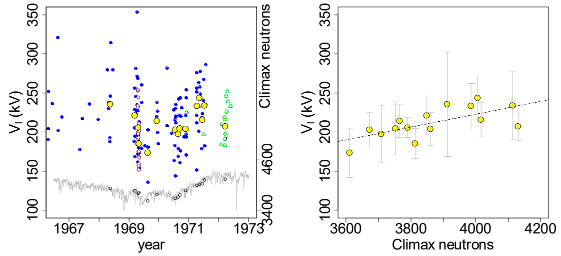
R.G. Harrison, M. Joshi, K. Pascoe, Inferring convective responses to El Niño with atmospheric electricity measurements at Shetland *Environ Res Lett* 6 (2011) 044028

60

60

External modulation of the global circuit – ionospheric potential

- Ionospheric potential (potential difference between ionosphere and surface – "V_I") can be found by integrating a vertical profile of the electric field
- A variation with galactic cosmic rays was demonstrated in Mülheisen and Markson's (independent) 1970s balloon and aircraft soundings of the ionospheric potential, with surface neutron monitor measurements of cosmic rays



R. G. Harrison and I. Usoskin, Solar modulation in surface atmospheric electricity *J. Atmos Solar-Terr Physics* **72**, 176-182 (2010)

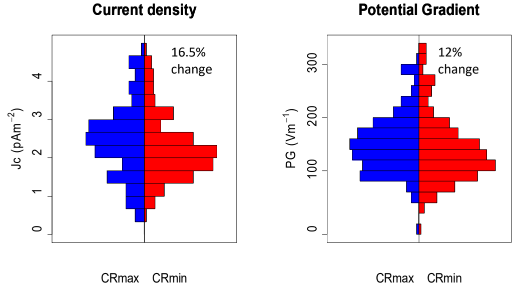
61

61

External (solar) modulation of the global circuit

Apparent in Lerwick surface measurements (1978-1985) of current density (J_c) and Potential Gradient (PG)

Solar variability effect is primarily via cosmic rays (CR) – "solar max" occurs at CR min and "solar min" at CR max



R. G. Harrison and I. Usoskin, Solar modulation in surface atmospheric electricity *J. Atmos Solar-Terr Physics* **72**, 176-182 (2010)

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5. Applications and planetary global circuits

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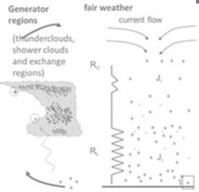
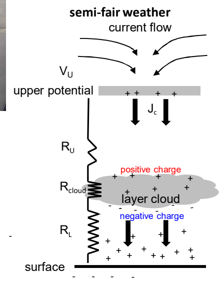
Global circuit also includes "semi-fair weather regions"

Layer clouds occupy about 30% of the planet's surface, and the current flow in the global circuit must pass through them – this **"semi fair weather" branch of the global circuit** has been largely neglected (until now)





Charging occurs at the **upper** and **lower** edge of layer clouds

R. Giles Harrison, Keri A. Nicoll, Evgeny Mareev, Nikolay Slyunyaev, Michael J. Rycroft, Extensive layer clouds in the global electric circuit: their effects on vertical charge distribution and storage *Proc Roy Soc A* 476: 20190758 (2020)

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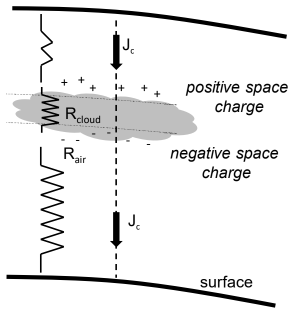
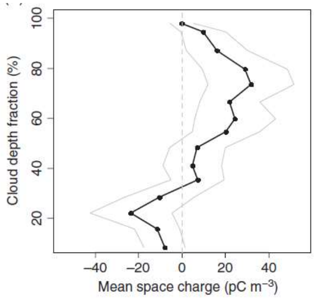
(a) Edge charging of extensive layer cloud

Is this widespread?

Layer clouds are common, and the global circuit is, well, global

Yes - mean profile determined from layer clouds measured in Finland, Antarctica and Reading





K.A. Nicoll and R.G. Harrison, Stratiform cloud electrification: comparison of theory with multiple in-cloud measurements *Quart Jour Roy Meteorol Soc* **142**, 2679–2691 (2016)

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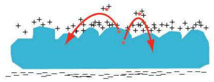
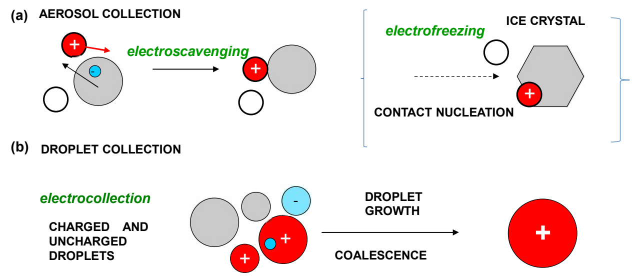
Possible effects of charged droplets on cloud processes



As our observations show, charge accumulates at upper and lower cloud boundaries on particles and droplets.

This may affect collision processes:



...and related effects on radiation reflection and emission, and precipitation

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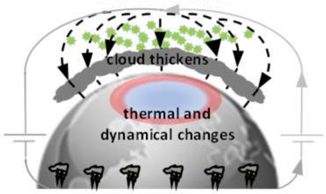
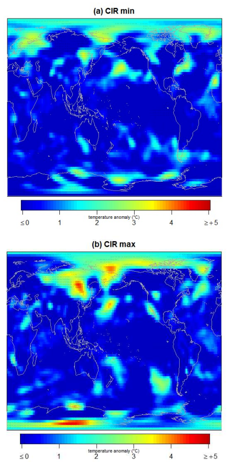
Evidence for a global effect on cloud



Temperature anomalies at 800m (NCEP)



- Current flow effect ought to occur in **both** hemispheres
- Expected to affect **extensive layers of low cloud**
- Low clouds act to keep warm air near the surface → **warm thermal anomalies**

Test using data in 2007/8, when cosmic ray ionisation increased regularly every 27 days, associated with a single sunspot (14 events)

R.G. Harrison and M. Lockwood, Rapid indirect solar responses observed in the lower atmosphere, *Proc Roy Soc A* 476: https://doi.org/10.1098/rspa.2020.0164 (2020)

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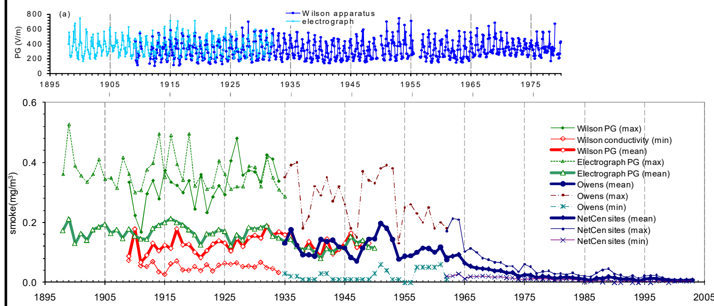
(b) Reconstruction of 20th century smoke pollution for Kew (semi-urban London)

Range of values from
- some direct smoke measurements (optical paper stain "Owens" method)
- Low concentrations - Conductivity measurements (Wilson)
- High concentrations - PG measurement (Wilson apparatus and Kelvin electrograph)



R.G. Harrison, Urban smoke concentrations at Kew, London, 1898-2004 *Atmos Environ* **40**, 18, 3327-3332, doi: 10.1016/j.atmosenv.2006.01.042

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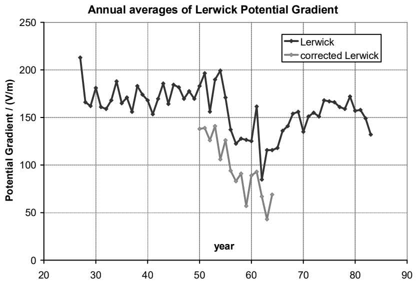
(c) Detecting releases of artificial radioactivity

…whichs causes increase in surface air conductivity



Radioactivity increases number of ions => Conductivity increases

$F = J_c/\sigma$

Annual averages of Fair Weather PG obtained at Lerwick, showing the period of atmospheric nuclear weapons testing 1956-1962.

(corrected values were derived by excluding "polluted" wind directions known to produce high PG measurements.)

Harrison, R.G., Twentieth century atmospheric electrical measurements at the observatories of Kew, Eskdalemuir and Lerwick *Weather* **58**, 11-19, (2003)

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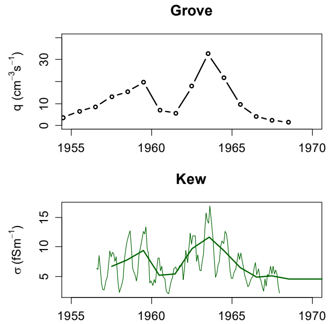
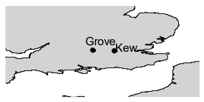
Observations of conductivity changes from radioactivity

Oxfordshire, direct measurements of ion production rate from ^{90}Sr

London, Wilson apparatus measurements of air conductivity





Gibson J.A.B, Richards J.E. and Docherty J. Nuclear radiation in the environment-beta and gamma ray does rates and air ionisation from 1951 to 1968. *JATP* **31**, 1183-1196 (1969)

R.G. Harrison and W.J. Ingram, 2005, Air-earth current measurements at Kew, London, 1909-1979 *Atmos Res* **76**, (1-4), 49-64

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Fukushima reactor accident

Release on 14th March 2011

Kelvin water dropper sensor

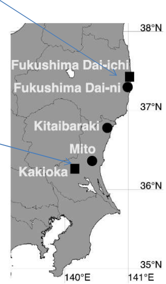

Figure 2. The locations of Fukushima Dai-ichi nuclear power plant (FNPP), Fukushima Dai-ni nuclear power plant (about 12 km south of FNPP), Kitaibaraki (about 70 km southwest of FNPP), Mito (about 130 km southwest of FNPP), and Kakioka (about 150 km southwest of FNPP).

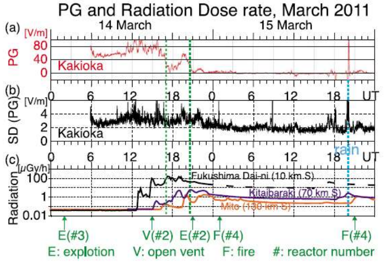

Figure 3. Two-day's data before and after the largest southbound release of the radioactive material from the Fukushima Dai-ichi nuclear power plant (FNPP) in March 2011: (a) 1-min averaged PG at Kakioka, (b) standard deviation of PG calculated from 1 Hz sampling data, and (c) 10 min resolution radiation dose rate data at three different stations between Kakioka and the FNPP. The green notes at the bottom denote incidents at the FNPP.

From Takeda et al, 2013, *Geophys Res Lett* 38, L15811, doi:10.1029/2011GL048511, 2011

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Planetary global circuits -remote detection requirements

sensing possibilities:

requirement	Charge generation		Lower conductive surface or region	Upper conductive region	Vertical current flow
	Electrical discharges	Precipitation			
Schumann resonances	✓		✓	✓	
Radar		✓	✓		
Broadband radio emission	✓				
Optical	✓				

Detection of vertical current flow within an atmosphere is not amenable to remote sensing… historically, terrestrial method has been to install surface electrodes

K.L. Aplin, R.G. Harrison and M.J. Rycroft, *Space Science Reviews* **137**, 11-27 (2008)

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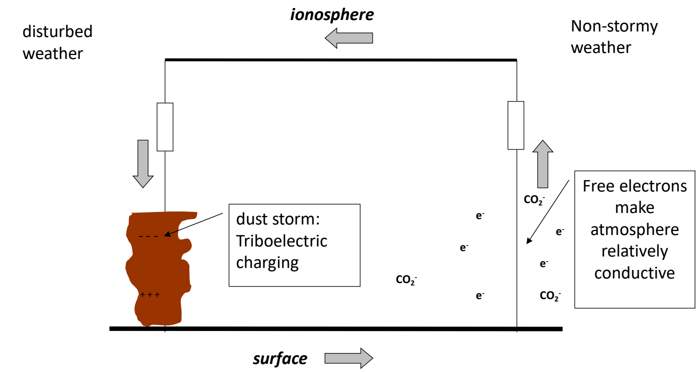
Martian global circuit: driven by dust?



From Aplin, Surv. Geophys. (2006), after Farrell and Desch JGR (2001), Fillingim (1998)

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Characteristics of the Martian global circuit

- Driven by discharges in dust storms
  - Two types of discharge predicted: “volcanic lightning” and also a weaker glow discharge
  - Strong seasonality (Farrell and Desch, *JGR*, 2001)
    - **In storm season, surface E = 475 Vm^{-1} and J_c = 1.3 nAm^{-2}**
    - **Outside storm season, surface E = 0.14 Vm^{-1} and J_c = 0.4 pAm^{-2}**
- **Current flow is in the opposite direction to Earth**
  - Atmospheric composition favours formation of CO_2^- ions and is tenuous enough for free electrons to exist
  - Interesting consequences of variable magnetic field
  - Surface conductivity is the major uncertainty for existence of global circuit
- No measurements yet
  - ExoMars “Franklyn” rover has radio sensors for lightning on Mars

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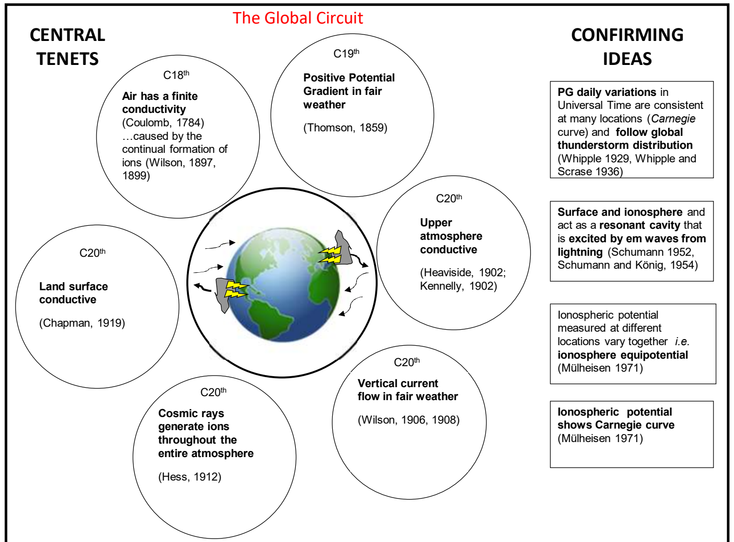

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Summary

•Wilson observed current flow and hypothesised a global circuit

•A similar diurnal variation in PG and thunderstorm area (the Carnegie curve) supports this

•Many observations can be explained by the framework of the global circuit concept, which links charge generation by thunderstorms to vertical current flow in the fair weather regions of the circuit.

•Current flow through “semi-fair weather” regions may influence clouds

•Other planetary global circuits may be available!

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